Investigations into the Influence of Generator Design on Rating of Circuit Breakers in a High Voltage Transmission Network

J. D. F. McDonald, *Member, IEEE*, and T. K. Saha, *Senior Member, IEEE*

***Abstract*--This paper examines the impact of the network modification produced by the replacement of an existing conventional generator with a high voltage directly connected generator on the adequacy of existing circuit breakers distributed throughout a high voltage transmission network. The significance of generator design changes is assessed by comparing the critical fault types producing maximal circuit breaker current through each breaker in the original and modified networks. In the majority of cases the impact of even significant generator design changes on the nature of these "critical fault types" is restricted mainly to breakers in the immediate vicinity of the generator of interest. Finally, analytical expressions quantifying the influence of generator design on the current flows produced by faults through circuit breakers distributed network-wide are developed to clarify the results obtained from simulation.**

***Index Terms*—Circuit Breakers, IEEE Standards, Powerformer^{TM}, power system faults, power generator planning**

I. Nomenclature

m – bus at which generator of interest connected to network
k – bus at which fault occurs
l – bus at remote end of line under consideration

II. Introduction

Circuit breakers form an integral part of the protective system for an electric power system. As stated in [1], satisfactory network behaviour is maintained under fault conditions through quick isolation of the faulted portion of the network, minimization of the available short circuit current and reducing the duration and extent of the outages by providing alternate circuits and automatic transfers. These objectives can be obtained only through correct selection and operations of circuit breakers throughout the network.

Any modification to network configuration may impact upon the adequacy of existing interrupting equipment. Given the considerable capital investment that must be allocated to these devices [2], the cost of any required breaker alterations or augmentation must be included in assessing of the cost effectiveness of any changes to network configuration. This is particularly pertinent when considering augmentation or replacement of existing generation capacity with generators of new or innovative design, such as Powerformer^{TM}, the high voltage generator developed by ABB in 1997 [3].

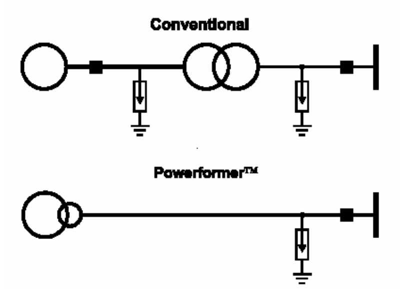

Fig. 1.Comparison of Powerformer^{TM} and conventional generator [3]

Powerformer^{TM} is able to generate electricity at transmission voltage levels and can inject power directly into the transmission network without need for a step-up transformer. Previous studies indicate that the fault current (amperes) produced by a three-phase fault at the terminals of the directly connected generator will be significantly reduced when compared with the corresponding fault at the terminals of the conventional generator while remaining comparable to the fault levels produced by a fault on the HV terminals of the generator step-up (GSU) transformer [3].

This paper, however, examines the impact of generator design on the fault types producing maximal current through a circuit breaker under fault conditions, thus determining the "critical fault type" of each breaker. This "critical fault type" can then be used in a formal breaker rating process, e.g. IEEE Std C37.010 1999 [4], leading to a thorough assessment of the impact of the replacement of an existing conventional generator and its (GSU) transformer by a directly connected generator of varying sub-transient reactance on the adequacy of existing network breakers.

As well as considering the variation in critical fault types determined by simulation of different network configurations, this paper also presents the derivation of an analytical technique for quantifying the potential impact of generator design variations upon the different fault types. This technique is then used to provide further insight into results obtained using conventional simulation procedures.

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III. Circuit Breaker Rating Procedures

The principal function of a circuit breaker as defined in [4] is to carry load current and interrupt short-circuit current. The time-dependent nature of power system short circuit behaviour means that these parameters can only be determined accurately by a dynamic stability study. A satisfactory estimate of fault behaviour can be determined through use of industry standards such as the IEEE C37 standards or IEC 60909 international standards. The standard techniques represent a compromise between solution accuracy and simulation simplicity [2] providing a conservative estimate of the parameters required for breaker application. The scope of this study was limited to the IEEE C37 standards, given their comparatively less complicated and perhaps more efficient solution procedure. [5]

A. *IEEE Standards*

The IEEE Standards C37.04 – 1999 [6], C37.06 -1997 [7] and C37.010 – 1999 [4] outline clearly the procedure for relating specific network conditions to required breaker ratings allowing selection of suitable breakers for each application. This investigation was confined to a consideration of only the short circuit current and related capabilities. The short circuit capabilities of a circuit breaker rated according to these standards is characterized by its *rated short circuit current.* This is defined in [6] as: "*the symmetrical component of short-circuit in rms amperes to which all required short-circuit capabilities are related*". By determining the impact of generator design on this parameter, the influence on parameters such as symmetrical or asymmetrical interrupting capability or rated closing and latching current carrying capability is also addressed.

1) Short circuit current calculation

The IEEE Standard C37.010 – 1999 outlines two methods for calculating the rated short circuit current. The basis of both methods is the calculation of the fault current E/X, where E represents the pre-fault voltage and X the equivalent network reactance at the fault point. Depending upon the level of accuracy required, this estimate either can be used directly or modified to account for ac and dc decrements. The required modifier depends upon the closeness of the fault to significant generation and the X/R ratio at the fault point.

IV. Assessment of Influence of Generator Designs on Critical Fault Types

A. *Relationship of Critical Fault Types and Breaker Ratings*

A limitation of the procedure outlined in C37.010 – 1999 [4] stems from the lack of consistency between the fault currents produced by bus faults and the actual line currents that must be interrupted by the circuit breakers [8]. Maximum breaker current is also dependent upon the breaker arrangements used in the network. Without specifying precisely the network-wide breaker locations maximal breaker current must be calculated by comparing at each breaker location the different fault current line flows as designated by

Line flow 1 current	*Line-out fault current*
Line flow 2 current	*Line-end fault current*

The different line currents are illustrated in Fig. 8 while the line-out and line-end fault are assumed to correspond to their standard definitions.

Different network configurations are required to calculate each fault type, ensuring that the values of E/X, X/R and the consequent ac and dc decrement multiplying factors will also differ, depending upon the critical fault type determined at a specific breaker location. It then can be assumed that a change in the critical fault type of a given breaker is potentially indicative of a change to breaker rating as calculated using IEEE Std C37.010 – 1999. Determining the number of circuit breakers whose critical fault type is affected by a network modification will provide an assessment of the suitability of existing circuit breakers for use in the altered network.

B. *Simulation Procedure*

In order to assess the influence of generator design on circuit breaker ratings an extensive fault study was completed on 600 bus transmission network modeling the transmission system used in Queensland, Australia. It was assumed that every line was equipped with a breaker connected at each end while each generator was also protected by a generator circuit breaker. This configuration represents more breakers than would be used in a realistic system but provides a clearer illustration of the regional impact of generator design changes.

The replacement of six different generators was considered, although results for only three different generators locations will be detailed. Figure 2 illustrates the comparison between the combinations of the sub-transient reactances of the conventional generators with short – circuit impedances of their GSU transformers to the sub-transient reactance of the analogous directly connected generators.

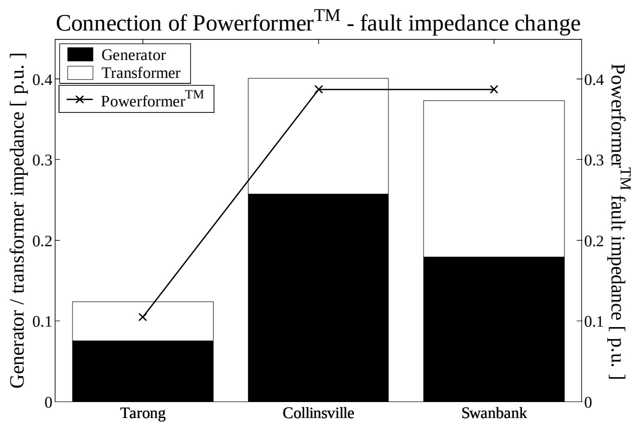

Fig. 2. Comparison of conventional generator / Powerformer™ fault impedances

The relationship illustrated is representative of that expected between the fault impedance of a conventional generator and a corresponding high voltage directly connected generator. The sub-transient reactance of the directly connected generator usually will be similar to or slightly lower than the total fault impedance of the conventional generator and GSU transformer replaced.

The most important step in the procedure was the comparison at all breaker locations of the magnitude of fault currents produced by each of the four fault types. The maximum fault current at each point defined the critical fault type that should be used to rate a specific breaker. This process was completed on the original network along with each of the modified network configurations considered.

C. Test Cases

The impact of changes to generator design on breaker rating is examined by simulating the following test cases.

1) Case 1

In the first case, the conventional generator and GSU transformer was replaced with a directly connected generator with fault impedance equal to the total fault impedance of the conventional generator and transformer replaced. This shows the impact of replacing a conventional low voltage – high current generator with a high voltage – low current generator.

2) Case 2

The second scenario involved replacing the conventional generator and GSU transformer with a realistically designed high voltage directly connected generator. The specific generator impedances used are illustrated in Fig. 2.

3) Case 3

In this case a short circuit was substituted for the conventional generator, with GSU transformer impedance left unchanged. This configuration illustrates both the maximum impact of changes to the conventional generator design in conjunction with illustrating the replacement of a conventional generator and GSU transformer with a directly connected generator of comparatively low fault impedance.

4) Case 4

For the final test case, the conventional generator and transformer were replaced by a directly connected generator of negligible fault impedance. Although this is not a realistic scenario, the results obtained illustrate the greatest impact of directly connected generator design on fault behaviour.

V. System Results

The results listed in Tables I – III include the number of breakers who critical fault types have been changed by each alteration of generator design. The italicised and bolded columns represent the critical fault types of the affected breakers in the original and modified networks respectively.

A. Case 1

TABLE I
CRITICAL FAULTS TYPES – CONVENTIONAL GENERATOR REPLACED WITH POWERFORMER™.

Fault Type	Tarong		Collinsville		Swanbank	
Line flow 1					*1*	**1**
Line flow 2			*1*		*1*	**1**
Line out				**1**		
Line end						

These results highlight the limited number of breakers at which the critical fault type will be affected by the change in generator configuration. At Collinsville a slight variation in the system in-feed to the breaker connected at what was formerly the GSU transformer high voltage terminals increases the significance of the line-out fault marginally. The magnitude of this variation however is not overly significant.

1) Conventional generator circuit breakers

The two breakers affected by the change in design of the Swanbank generator are the conventional generator circuit breaker and a circuit breaker on the low voltage terminal of the original step-up transformer. The identity of these breakers has been retained in the directly connected system although in a realistic network these breakers would be removed or replaced as a result of the radical change to generator terminal fault current (amperes) produced in the modified network. The fault current produced by an earth fault on the directly connected generator terminal would also exceed the permissible levels for a generator circuit breaker rated according to IEEE Std C37.013-1997. [9]

Perhaps it is more appropriate to note the lack of change to the rating of the breaker formerly at the high voltage terminal of the GSU transformer that would become the generator circuit breaker in the directly connected system.

B. Case 2

TABLE II
CRITICAL FAULTS TYPES – CONVENTIONAL GENERATOR REPLACED WITH REALISTIC POWERFORMER™.

Fault Type	Tarong		Collinsville		Swanbank	
Line flow 1					*1*	**1**
Line flow 2			*1*		*1*	**1**
Line out				**1**		
Line end						

The results of Table II again emphasize the limited change to critical fault types produced by the introduction of a more realistically designed directly connected generator.

Although the fault in-feeds of the directly connected generators were more pronounced than that of Case 1, the proximity of the generator to the meshed transmission system ensured that the rating of breakers attached to the high voltage generator terminals and surrounding lines would be dominated by the system contribution. At these points critical fault types were unaffected by the different high voltage generator design.

C. Case 3

TABLE III
CHANGE IN CIRCUIT BREAKER CRITICAL FAULTS – CONVENTIONAL GENERATOR REMOVED.

Fault Type	Tarong		Collinsville		Swanbank	
Line flow 1	*1*	**2**	*1*	**2**		
Line flow 2	*1*	**1**	*1*	**1**		
Line out	*1*					
Line end			*1*			

As highlighted previously, the interpretation of the results obtained in this case will depend on the manner in which the reduction in conventional generator fault impedance is viewed.

If the network modification is viewed as a reduction in fault impedance of the existing conventional generator then it would appear that the influence of the conventional generator on circuit breaker ratings is fairly limited. The majority of change is confined to breakers located near the generator terminals with the variation in critical fault type due mainly to the increased significance of generator fault in-feeds.

If this network change however is considered as the replacement of a conventional generator and GSU transformer with a directly connected generator of reduced sub-transient reactance then it would appear that even this large change to generator design does not lead to a comparably large change to the critical fault types of breakers in the modified network. As highlighted above, the breakers where change is most pronounced are those at the terminals of the LV generator. These breakers would be removed in the directly connected configuration. More importantly, the appreciable increase in generator fault contribution still does not affect the breakers connected at what was originally the HV terminal of the GSU transformer, as they remain controlled by system fed faults.

The large change to generator design however did highlight the significant regional influence of both conventional and directly connected generators on network fault behaviour. The generator design variation at both Tarong and Collinsville lead to changes in the critical fault types of breakers over 150 km away from the generator terminals, although the actual change to the short circuit current ratings was limited to around 2%.

D. Case 4

The final change to generator design considered represents the most significant network modification that could be produced by the introduction of a directly connected generator. While these results obtained are somewhat un-realistic the trends illustrate the expected impact of replacing the existing conventional generator/transformer by a directly connected generator with very low fault impedance.

As can be seen in Fig. 3 and Fig. 4, the introduction of the low impedance directly connected generator produces a change in critical fault types at a number of breaker locations.

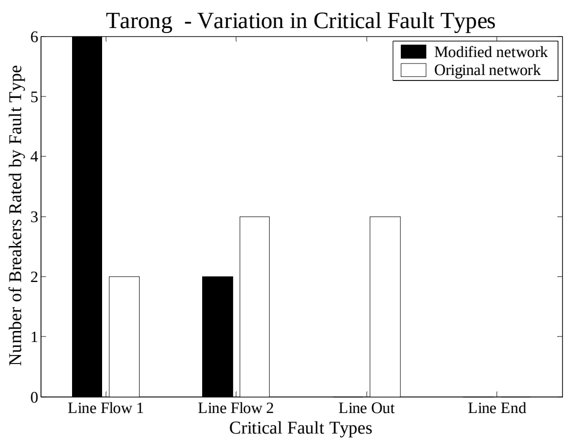

Fig. 3. Change in critical fault types – Conventional generator at Tarong replaced with S/C directly connected generator

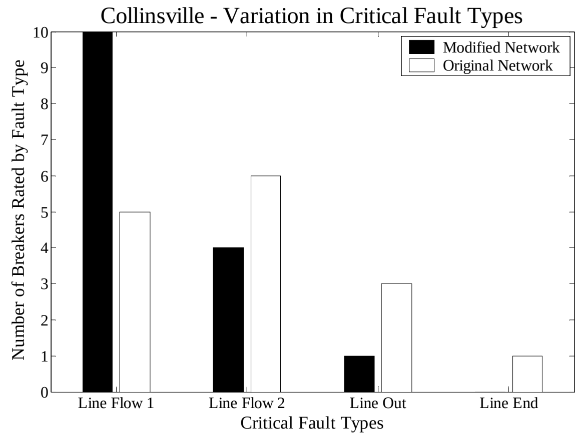

Fig. 4. Change in critical fault types – Conventional generator at Collinsville replaced with S/C directly connected generator

The significant impact on critical fault types was observed mainly for breakers located on lines relatively near to the directly connected generator. The change in critical fault type was often due to the increased fault current in-feed from the directly connected generator. In several cases however the breakers affected were not geographically close to the generator. In these cases it appeared that the increased line-flows in the modified network placed a greater significance on line flow rather than line-out or line-end faults.

VI. Analytical Assessment of Influence of Generator Design on Fault Currents

Although the results obtained suggest that impact of the replacement of a conventional generator with a directly connected generator is relatively limited, a more analytical approach is required to determine the specific network conditions that control this phenomenon. Of particular consequence would be the identification of those system configurations where even small changes in generator design would place pressure on the adequacy of existing breakers.

In earlier work by the authors [10, 11] analytical expressions were defined that illustrate the degree of influence that the design of either a single conventional or directly connected generator exerts upon the bus fault currents produced at points throughout a high voltage transmission network. Similar expressions could also be obtained that quantify the influence of generator design upon the fault quantities needed for circuit breaker rating including the line currents produced under fault conditions and the line – out or line – end fault currents.

Simple expressions can be developed for the impact of generator design on line currents. This is confirmed in the brief derivation of the required equations in the attached appendix.

It was not possible to derive similar concise equations for line–out and line–end faults currents. Instead the system modifications required for calculating these fault currents were first applied to the network from which the influence of the generator of interest had been completely removed. It was then possible to obtain numerical solutions to the equation:

$$I_f^{(k)} = \frac{V_k}{Z_{kk}} \frac{\{(Z_G + Z_T) + Z_{mm}\}}{\left\{(Z_G + Z_T) + \left(Z_{mm} - \frac{Z_{km} Z_{mk}}{Z_{kk}}\right)\right\}} \quad (1)$$

This characterizes the influence of generator design on line-end and line out fault currents. The validity of this approach was verified by comparing the maximum potential variation in the line-out and line-end fault currents calculated from manipulation of equation (1), as using a method described in [10], with the ratio of the fault currents determined from simulation of the test system with the fault impedance of the generator of interest either very large or else approximately equal to zero. The comparison is shown in Fig. 5

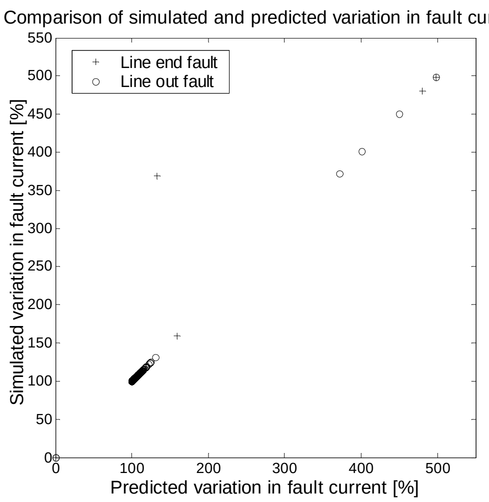

Fig. 5. Comparison of predicted and simulated line-out/line-end fault currents

A. Comparison with analytical results

A logical application of the analytical technique is identification of the range of generator designs leading to significant change to network fault behaviour. From an analogy with control systems theory it would be expected that the major change in network response would be produced by generator designs varying between the relevant break points determined for each different fault parameter. These ranges of these break points for the connection of high voltage generator at either Collinsville or Tarong are shown in Fig. 6 and Fig. 7.

The proximity of the break points to the origin is quite obvious especially for a directly connected generator at Tarong. This implies that significant variation in network fault behaviour would not be expected unless the fault impedance of generator of interest was also quite small, an interpretation consistent with the results obtained previously. Consequently the relatively minor change in generator fault impedance produced by the inclusion of a realistic directly connected generator such as Powerformer™ would be unlikely to produce significant changes to the critical fault types of the network breakers. Significant impact would be produced only if the break points were widely separated, as would be the case in a network that was both relatively un-meshed and contained little additional generating capacity. In this case the inclusion of a directly connected generator could have a marked impact on the breakers critical fault types.

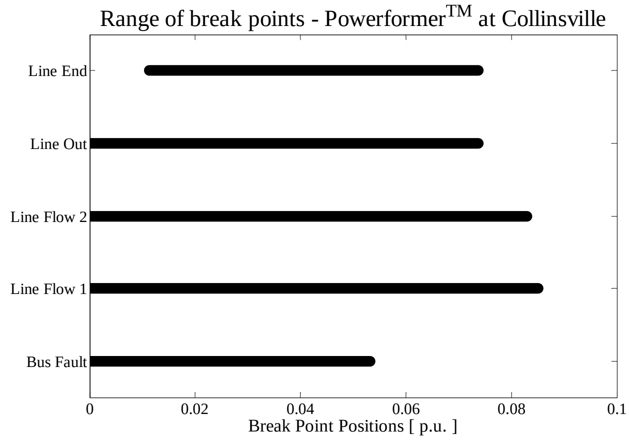

Fig. 6. Break points ranges – Powerformer™ at Collinsville

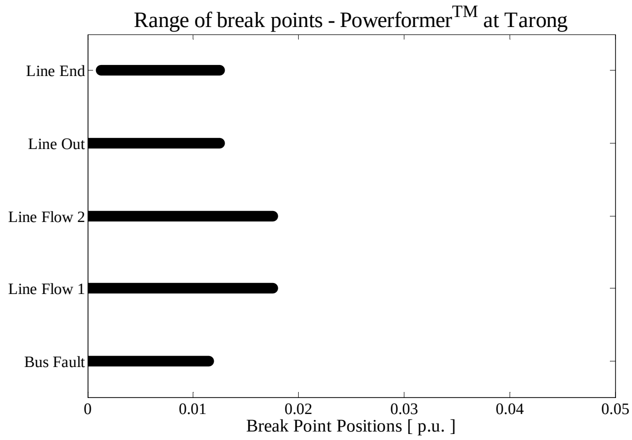

Fig. 7. Break points ranges – Powerformer™ at Tarong

In [10, 11] a proportional relationship between break point separation and fault parameter sensitivity was also highlighted. The larger range of break points for the line flow currents shown in Fig. 6. and Fig. 7. then suggests that these parameters could be more sensitive to generator design than the other fault parameters This postulate is supported by the increase in the number of breakers rated by line flow currents rather than line-end or line-out fault current in network containing a low impedance directly connected generator.

VII. Conclusions

The most important finding of the investigation is the relatively limited impact produced by the replacement of a conventional generator with a directly connected generator on the critical fault types governing circuit breaker ratings in a realistic power system. This suggests that very few modifications will be required to breaker capacity to allow the inclusion of a high voltage generator into an existing system where the original breakers have been rated according to C37.010 – 1999. Even large changes to generator design appear to have an impact on only a limited number of breakers, although the location of the affected breakers will not necessarily be confined to the direct vicinity of the generator under consideration.

These results also highlight the effectiveness of the analytical technique to predict accurately the potential impact of generator design variation on fault parameters such as line-out and line-end fault currents. The analytical method also appears to provide a logical explanation for the numerical results obtained, allowing identification of system configurations that are highly sensitive to generator design.

Finally, although this investigation suggests that the design of a single directly connected generator would have only a limited impact on critical fault types required for short circuit current rating calculations, this represents only one aspect of the circuit breaker rating process. Properties such as switching capability or transient recovery voltage have not been addressed. Future work however will concentrate on the remaining facets of the circuit breaker short circuit rating procedure including consideration of single line-to-ground faults and a more detailed treatment of AC and DC decrement.

VIII. Appendix

A. Generator influence on line flow fault currents

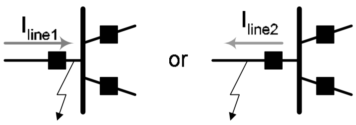

Fig. 8. Breaker line flow fault currents

1) Line flow 1

The current through the line between bus *l* and the fault bus *k,* shown as I_{line1}, can be determined by:

$$I_{line1} = \frac{dV_l - dV_k}{Z_{line}} = \frac{(-I_f)Z_{lk,new} - (-I_f)Z_{kk,new}}{Z_{line}} \qquad (2)$$

where $Z_{lk,new}$, $Z_{kk,new}$, represent elements of the impedance matrix incorporating the impact of generator design. The impact of generator design can also be represented by expressing (2) in terms of both impedance matrix elements describing a network from which the influence of the generator has been completely removed along with the fault impedance of the generator of interest.

$$I_{line1} = \frac{(-V_k)(Z_{lk} - Z_{kk})}{Z_{line}(Z_{kk} + Z_f)} \frac{\left\{Z_G + Z_{mm} - \frac{Z_{lm}Z_{mk} - Z_{km}Z_{mk}}{Z_{lk} - Z_{kk}}\right\}}{\left\{Z_G + Z_{mm} - \frac{Z_{km}Z_{mk}}{Z_{kk} + Z_f}\right\}} \qquad (3)$$

where V_k is the pre-fault voltage at bus *k*.

This expression is analogous to those relationships defined in [10, 11], suggesting that the impact of the generator fault impedance on I_{line1}, the current through the breaker, will be controlled by the location of break points extracted from (3).

2) Line flow 1

A similar derivation can be completed for line flow 2.

$$I_{line2} = \frac{(V_k)(Z_{line} + Z_{lk} - Z_{kk})}{Z_{line}(Z_{kk} + Z_f)} \frac{\left\{Z_G + Z_{mm} - \frac{Z_{lm}Z_{mk} - Z_{km}Z_{mk}}{Z_{line} + Z_{lk} - Z_{kk}}\right\}}{\left\{Z_G + Z_{mm} - \frac{Z_{km}Z_{mk}}{Z_{kk} + Z_f}\right\}} \qquad (4)$$

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X. Biographies

John McDonald (M'2001) was born in Brisbane, Queensland, Australia, on October 21, 1977. He obtained a BE (Hons – Elec)/BA (Chinese) from the University of Queensland in 1999 and at present he is completing for his PhD investigation at the University of Queensland entitled "Investigations into the design of Powerformer^{TM} for optimal generator and system performance under fault conditions." His fields of interest include power systems analysis, system fault performance and equipment condition monitoring.

Tapan Kumar Saha was born in Bangladesh and came to Australia in 1989. Dr Saha is a Senior Lecturer in the School of Information Technology and Electrical Engineering, University of Queensland, Australia. Previously he taught at the Bangladesh University of Engineering and Technology, Dhaka, Bangladesh for three and a half years and at James Cook University, Townsville, Australia for two and a half years. He is a senior member of the IEEE and a Chartered Professional Engineer of the Institute of Engineers, Australia. His research interests include power systems, power quality, high voltage and insulation Engineering.